# Thermal control of SUNRISE, a balloon-borne solar telescope

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**Abstract:** SUNRISE is a balloon-borne solar telescope flown with a long-duration balloon by NASA's Columbia Scientific Balloon Facility team from Esrange (Swedish Space Corporation), on 8 June 2009. SUNRISE has been a challenging mission from the thermal point of view because of its size and power dissipation. Thus, a dedicated thermal analysis has been carried out to find a solution that allows all the devices to be kept within their appropriate temperature ranges, without exceeding the allowable temperature gradients, critical for optical devices. In this article, the thermal design of SUNRISE is described. A geometrical mathematical model and a thermal mathematical model of the whole system have been set up for the different load cases in order to obtain the temperature distribution and gradients in the system. Some trade-offs have been necessary to fulfil all the thermal requirements. The thermal hardware used to achieve it is described. Finally, the temperatures obtained with the models have been compared with flight data.

## 1 INTRODUCTION

SUNRISE is balloon-borne solar telescope whose main scientific goal is to study the structure and dynamics of the magnetic field in the Sun's atmosphere. It is the biggest solar telescope ever flown in a stratospheric balloon mission. Solar observations from Earth suffer from important limitations, for instance, part of Sun's UV radiation is not accessible from ground because of the Earth's atmosphere absorption, and atmospheric turbulence degrades the quality of images, causing blurring. This is why high-resolution observations are usually conducted from space. The use of a stratospheric balloon as a vehicle to carry solar telescopes reduces mission costs drastically, and has the advantage of observing the Sun above 99 per cent of the Earth's atmosphere. The telescope has an aperture of 1 m, which allows spatial resolutions never obtained before from ground during time intervals of hours to days. SUNRISE has taken images of the magnetic structure and provided measurements of the magnetic field, the flow velocity, and thermodynamic properties of plasma with an unprecedented resolution on the solar surface [**1**, **2**]. This will allow the scientists to better understand the structure and dynamics of the magnetic field in the atmosphere of the Sun. A brief description of SUNRISE is given in the next section. SUNRISE is an international project led by the Max-Planck-Institut für Sonnensystemforschung (MPS) in Katlenburg-Lindau (Germany) with the participation of other European and American research institutes: Kiepenheuer-Institut für Sonnenphysik (KIS) in Freiburg (Germany), High Altitude Observatory (HAO-NCAR) in Boulder (USA), Instituto de Astrofísica de Canarias (IAC) in

Tenerife (Spain), Instituto Astrofísico de Andalucía (IAA-CSIC) in Granada (Spain), Instituto Nacional de Técnica Aeroespacial (INTA) in Madrid (Spain), Instituto de Microgravedad Ignacio Da Riva-Universidad Politécnica de Madrid (IDR/UPM) in Madrid (Spain), and Grupo de Astronomía y Ciencias del Espacio-Universidad de Valencia (GACE) in Valencia (Spain).

At an altitude of 38 km in the polar summer, constant Sun observation is possible as no night periods occur, with practically the same conditions of observation as from outer space. From the thermal point of view, since the air at this floating altitude is very rarefied, the external pressure being about 300 Pa, the environment of the payload is very similar in terms of heat transfer to space environment, where thermal interactions are dominated by radiation. The main difference with regard to space missions is the presence of uncompensated gravity forces. Therefore, natural convection occurs within pressurized vessels.

Although SUNRISE was initially planned to be flown from McMurdo Station in Antarctica, due to logistic and financial reasons, the launch site was moved to the Arctic area. SUNRISE was finally flown on 8 June 2009 from Esrange Space Center, a Swedish Space Corporation launch facility. The launch was conducted by the American balloon launch team from NASA's Columbia Scientific Balloon Facility (CSBF), as part of their Long Duration Balloon programme. At float altitude, the balloon, zero pressure type, expanded to 34 MCF (million cubic feet), about 130 m in diameter. During the summer, the stratospheric winds carry the balloon westwards at nearly constant latitude with permanent sunshine. Hence, the flight was terminated 6 days later, with SUNRISE landing on Somerset Island, northern Canada. The trajectory followed by the balloon has been plotted in a map and is shown in Fig. 1. The data storage system (DSS) was recovered by CSBF and MPS personnel and transported to Germany for its analysis. During the flight, SUNRISE collected data with unprecedented resolution. Therefore, the mission can be considered a complete success.

A previous test flight of SUNRISE had already been conducted on 3 October 2007. That balloon was also launched by the CSBF team, in that case from Fort Sumner (New Mexico, USA). Test flight measurements, as will be explained below, were used to improve the design.

The SUNRISE project has been managed to some extent as a space mission. Thus, a dedicated thermal analysis was carried out aiming to keep all the devices within their appropriate temperature ranges, and to guarantee that the allowable temperature gradients were not exceeded throughout the mission. The initial high power requirements of the mission, a continuous payload power of 1.8 kW (final design was 1.3 kW), together with the harsh environment at 38 km (almost vacuum environment, very high Earth albedo coefficient over ice and permanent solar irradiation) made SUNRISE a quite challenging mission from the thermal point of view. Thermal finishes, equipment layout, radiator sizes, etc., were chosen so that all the thermal requirements were met. This article reports SUNRISE thermal control design. The thermal designs of the main systems

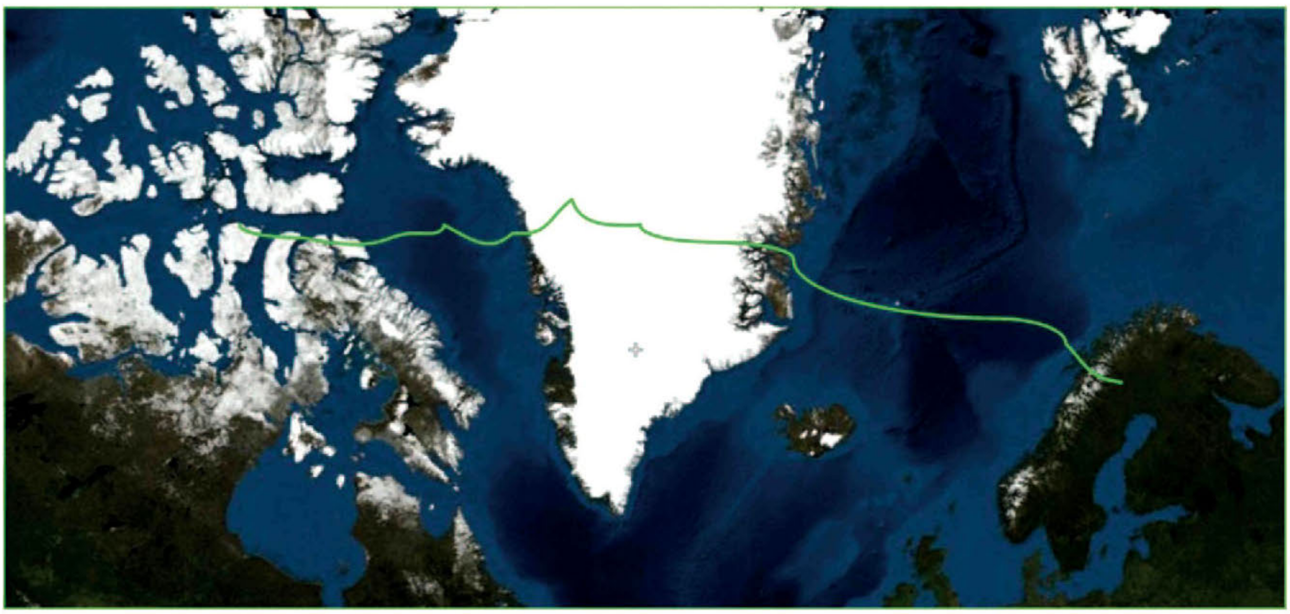

**Fig. 1** Trajectory followed by SUNRISE from Esrange (Sweden) to Somerset Island (Canada)

are described, highlighting the problems encountered during the design process and the solutions found. Finally, the solutions obtained from the models are compared with flight data, where main discrepancies have been identified.

## 2 SUNRISE

As already indicated above, SUNRISE, with a mass of 1.920 kg, is the biggest solar telescope flown in a balloon mission. However, the total mass of the mission is considerably higher. Hence, the balloon film has a mass of 2.330 kg, the helium filling it 500 kg, and the auxiliary equipment, such as suspension, parachute, etc., and the ballast used for altitude stabilization, a mass of 544 kg.

The main elements SUNRISE consists of are: the telescope, the post-focus instrumentation (PFI), the electronics racks, the DSS, the solar panels, the system instrumentation package (SIP), and the gondola. A CAD view of SUNRISE can be seen in Fig. 2, with the main elements indicated on it. Figures 3 and 4 are front and back photographs of SUNRISE taken just before the launch.

SUNRISE is a Gregory-type telescope with almost 25 m of effective focal length and a parabolic primary mirror, made of Zerodur with 1-m diameter. A field stop is placed in the primary focus. Hence, a heat rejection wedge (HRW) reflects 99 per cent of the light and defines the usable field of view. After the secondary mirror, the light is folded back by two flat mirrors to feed the PFI. An important issue from the thermal point of view is that only 10 W out of the initial 1 kW incoming to the telescope primary mirror eventually arrive to the PFI.

SUNRISE's PFI consists of a stiff honeycomb structure and optical bench with two instruments and auxiliary equipment on it. Sunrise Filter Imager (SuFI) is a camera sampling the photosphere and chromosphere in the UV and visible spectral ranges. Imaging Magnetograph eXperiment (IMaX) provides two-dimensional maps of the complete solar magnetic

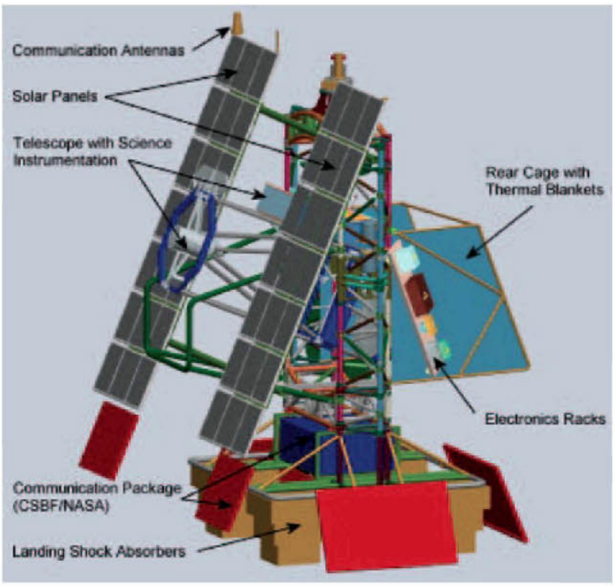


**Fig. 2** CAD view of SUNRISE with the main systems indicated on it. Note: wind shields and telescope Sun shield have been removed

**Fig. 3** Photograph of SUNRISE (front view) just before launch

**Fig. 4** Photograph of SUNRISE (back view) just before launch

vector and of the line-of-sight velocity. The Image Stabilization and Light Distribution (ISLiD) allows simultaneous observations with SuFI and IMaX. Finally, the correlation wavefront sensor controls a fast tip-tilt mirror of ISLiD. A third camera, SUnrise POlarimetric Spectrograph (SUPOS), was initially planned, but it was not finally flown due to programmatic reasons.

Two electronics racks are mounted symmetrically on the left and right of the gondola structure. One contains the main electronics for the PFI, and the other the electronics for the gondola system. Commercial off-the-shelf components have been used whenever possible. For this reason, some of the electronics boxes are pressurized. The racks are tilted in two axes for thermal reasons: to decrease the albedo and Earth infrared (IR) thermal loads and to increase the view factor with respect to outer space. They are also located behind the solar panels to avoid direct Sun illumination on its back surface.

The gondola used to house the telescope and the PFI is a complex structure made of aluminium and steel. It provides the appropriate stiffness and dimensional stability for all the optical devices. The elevation of the telescope needed to point to the Sun is achieved by means of two (coarse and fine) drives. The azimuth is controlled using a momentum transfer wheel unit located at the top of the gondola. The gondola also houses, and is used as a mounting structure for, other important parts. The power is supplied by two $5 \times 1\ m^2$ silicon solar panels providing approximately a continuous power of 1.3 kW. They are mounted with a fixed inclination of 23°, as the Sun elevation is expected to change between 0° and 45°. Two Lithium-ion battery packs with a total capacity of 5 kWh are used for the ascent, the phase where the system is not pointing to the Sun and therefore, the solar panels do not provide the energy necessary to feed the systems. The DSS consists of two pressurized cylinders with the hard drives inside. Aiming to prevent any damage during the landing, they are located within the gondola frame. Finally, the balloon SIP, controlling the balloon operation is located under the gondola. It is under the responsibility of NASA's CSBF. A more detailed description of SUNRISE configuration, system description, and mission can be found in Barthol *et al.* [**3**, **4**].

## 3 SUNRISE THERMAL DESIGN

As mentioned above, SUNRISE has been designed and managed in a manner similar to a space system; so the normal procedures followed for the thermal design of a spacecraft have been applied. Extreme hot and cold cases for the cruise phase have been identified, and steady hot and cold temperatures have been calculated for those load cases. This is a conservative approach; real temperatures are expected to change within that range throughout the mission. In the cruise phase, the thermal interactions with the environment are merely radiative because the magnitude of outer pressure is only a few millibars, and therefore convection is negligible. During the ascent phase, lasting about 3 h, the system behaves in a manner that is totally different from the thermal point of view. A continuously changing convective cooling occurs, with the risk of subcooling of the systems while passing through the cold tropopause. This case was identified as thermally critical during SUNRISE test flight in 2007. Then, a dedicated transient analysis was devoted to this phase [**5**], and measures to avoid equipment reaching too low temperatures were adopted, as will be explained below.

### 3.1 Load cases

The extreme environmental cases [**6**], between which SUNRISE is expected to be during the cruise phase are defined by the following.

Hot case:

(a) solar flux: 1397 $W/m^2$;
(b) Earth blackbody equivalent temperature: 258 K (IR radiation of 250 $W/m^2$);
(c) albedo coefficient: 0.95 (maximum with snow and ice);
(d) Sun elevation angle: 43° (maximum at latitude 70°, 21 June).

Cold case:

(a) solar flux: 1392 $W/m^2$;
(b) Earth blackbody equivalent temperature: 229 K (IR radiation of 156 $W/m^2$);
(c) albedo coefficient: 0.63 (worst case cold albedo/Earth flux combination);
(d) Sun elevation angle: 0°.

Note that minimum albedo coefficient occurs over the oceans (about 11 per cent of Sun reflection). However, in that case, Earth IR radiation is close to that defined for the hot case. Hence, the worst cold case has been identified when the balloon is flying over clouds, whose blackbody equivalent temperature is much lower than the oceans'. In any case, regardless of the albedo coefficient chosen to define the cold case, the Sun elevation angle of 0° for the cold case means that the albedo thermal load is practically negligible when compared to the other thermal loads (the angle between Sun's rays and SUNRISE nadir line is 90°).

### 3.2 Thermal design

The philosophy of the thermal control of SUNRISE was to obtain a thermal design as simple as possible, mainly passive, with the use of heaters for those elements that could reach too low temperatures. As in most thermal control systems, it was aimed to diminish the effects of the environment changing conditions on the system temperatures. This is achieved using low $\alpha/\varepsilon$ coatings, that is, coatings with a low absorption coefficient for solar radiation and a high IR emissivity. This is especially necessary for Antarctic or Arctic balloon missions because in steady hot conditions, the high albedo coefficient over ice and the permanent Sun illumination makes it necessary to use white coatings to prevent the surfaces from too high temperatures. Hence, most of Antarctic or Arctic missions have white or highly reflective coatings as, for instance, the Antarctic impulsive transient antenna (ANITA) [**7**] or the Japanese–American cosmic ray emulsion chamber experiment (JACEE) [**8**]. Therefore, in this case, white paint Aeroglaze 276 has been used for most surfaces. Those elements that are still hot with white paint have been covered with silver Teflon tape, with a lower $\alpha$ coefficient than the white paint.

Apart from the telescope, the most demanding subsystems from the thermal point of view are the PFI, the electronics racks, and the DSS. A brief description of the thermal design of each subsystem is presented in the following subsections.

*3.2.1 Telescope.* The telescope has been designed and integrated by the German company Kayser-Threde under contract with MPS and following their specifications. The thermal analysis of the telescope has been carried out together with a finite-element model to evaluate the mechanical deformation and with an optical study to assess the primary mirror wavefront error. The main mirror, made of Zerodour, has been manufactured by SAGEM in France. It is cooled by radiating energy from its back surface to the cold environment. To increase the view factor with cold sky and decrease albedo and Earth IR radiation, three adjustable blades are mounted on that side. The inner surfaces of the blades are coated with VDA (vacuum-deposited aluminium) kapton and the outer ones are painted white.

The front side of the primary mirror reflects nearly 1 kW of solar radiation, which is concentrated on a disc of 22-mm diameter. A HRW is used to reflect most of this energy allowing only 10 W to reach the science instrumentation. The cooling of the HRW is performed using two ammonia heat pipes that connect the hot surface to two radiators, covered with optical solar reflectors. They are fixed in such a way that the condenser is always above the evaporator to take advantage of gravity forces.

The telescope is located within a cage covered with three-layer thermal blankets acting as radiation shields. The external layer is a VDA mylar foil, of 125 μm (5 mil) thickness, with the mylar on its outer face. The intermediate layer is a flexible foam that provides mechanical strength. Finally, the inner layer is beta-cloth for the front part of the cage (seeing the front face of the primary mirror) and high-reflective VDA kapton (VDA outside) for the rear side (seeing the back face of the primary mirror and the cooling blades), enhancing the cooling of the primary mirror in this way.

*3.2.2 Electronics racks.* SUNRISE's electronics boxes are mounted on two honeycomb plates (aluminium skins 0.5-mm thick, standard hexagonal aluminium cell core 50-mm thick) $1 \times 2$ m$^2$ each, acting as radiators. The proper operation of electronics requires that the maximum temperature on the housing does not exceed 40 °C and does not drop below −10 °C during the cold case. In order to increase the view factor with outer space, the electronics racks have been placed in the sides of the gondola, tilted in two axes (30° around a vertical axis and 20° around a horizontal one) to diminish radiation input from Earth (both IR and albedo) and to avoid being heated by the solar panels. Thermal fillers have been used to enhance heat transfer between the most dissipative boxes and the rack. Early in the design process, the power dissipated by the PFI electronics was foreseen to be almost 400 W. As the project evolved, that figure was reduced to 240 W. To avoid subcooling of those boxes with lower power dissipation than that initially expected, when the design was refined, part of their surfaces were covered with foam pieces in order to block radiation to outer space.

The test flight carried out to verify the proper functioning of the systems and among other things the thermal design was conducted in Texas in October 2007, as already mentioned. Very useful information and some lessons were learnt from this flight. It showed that the pass through the tropopause yields too low temperatures in the external boxes subjected to convective cooling. The measured external air temperature was then −70 °C (detailed measured profiles can be found in Pérez-Grande *et al.* [**5**]), which combined with a velocity of about 4 m/s, led to a forced convection heat transfer that cooled down the equipment under the allowable limits. To prevent this, the initial design was modified and *wind shields* that protect the equipment from the convective cooling have been used for the science flight. Since the thermal design was proved to be working properly during the cruise phase, a material that hardly affected the thermal conditions at float altitude was selected. Thus, linear low-density polyethylene (LLDPE) film, 1.5-mil thick, was selected as the most appropriate material to cover and shield the electronics from wind. It has a transmissivity of 0.814 in the IR and 0.914 in the visible, which allows the electronics boxes to be practically in the same thermal conditions as without the film during the cruise. The measured properties of the film were kindly provided by personnel of NASA Balloon Program Office. This way, the problem of the cooling during the ascent was solved without adverse effect on the current design. A picture of the electronics rack with the protective shield can be seen in Fig. 5.

It has to be noticed that this way of protecting the electronics during the ascent is quite a novelty. Electronics onboard balloon payloads are usually protected against the environment either by locating them within a closed box or by wrapping the electronics racks with a material that blocks radiation such as mylar cloth or beta-cloth. This method can be used when the power dissipation of the boxes is not very high. Unfortunately, this frequent solution could not be used in the case of SUNRISE because the electronics boxes needed direct view of outer space, in order to radiate energy to a cold sink. Hence, the material selected, LLDPE, practically transparent to IR radiation, allowed the electronics to radiate to space to be at the proper temperature.

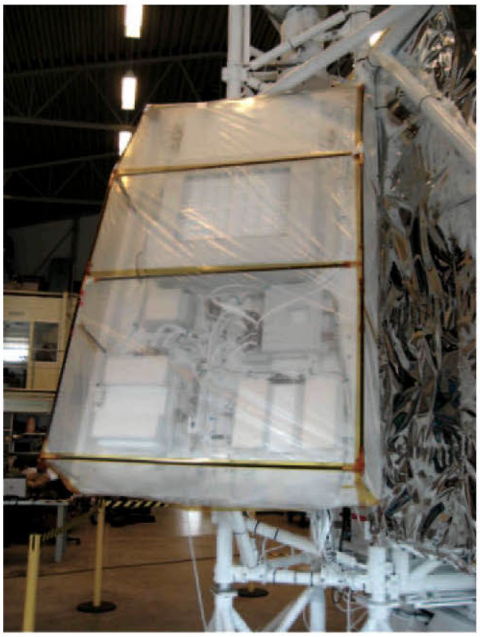

**Fig. 5** PFI electronics rack with the wind shield

*3.2.3 Post-focus instrumentation.* The PFI structure is a honeycomb (CFRP skins 1.25-mm thick, aluminium cell core 30-mm thick) frame 2 m $\times$ 1 m with three compartments where the scientific instruments are located. The bottom panels are also honeycombs but thinner than the frame ones (CFRP skins 0.5-mm thick, aluminium cell core 10-mm thick).

The aim of the thermal design for this part of the system is to keep this structure at $20\pm10\,^{\circ}$C for the whole mission. This requirement is given for the dimensional stability of the platform where most optical devices are mounted. This is a strong thermal constraint for several reasons. First, one side of the long structure is facing the Sun and the other part is seeing the cold space. Second, the most dissipating devices are sitting in this hot part of the structure. Third, the thermal conductivity of a honeycomb structure is rather low. These three facts have made the design of this part quite difficult. In order to achieve the specified thermal stability regardless of the environmental conditions, the following measures were adopted. First, the front side of the PFI, that is, the side facing the Sun, is protected with a Sun shield to reduce the solar heat loads into the system. The Sun shield front side is painted white. This way, not only are the loads reduced but also the thermal gradients limited. Second, the PFI structure is insulated with closed-cell foam wrapped with VDA mylar. The foam has insulation purposes and the VDA mylar is used to guarantee the cleanliness required by optical devices and a highly reflective thermal finish. Hence, the power dissipated by the PFI equipment as well as the external loads do not affect the structure and the required dimensional stability is achieved. For the PFI high dissipating devices, dedicated radiators are used. Depending on the dissipation, the radiators are coated with Aeroglaze A276 white paint or with silver Teflon tape for the most demanding devices.

Due to a delay in the project, for programmatic reasons, part of the PFI had to be manufactured when the design of other parts was still not frozen. To avoid problems in the already manufactured devices, the radiators were slightly oversized. Their sizes were adjusted once the design was frozen and refined. Instead of cutting the unnecessary surfaces, for simplicity, they were covered with foam pieces to block radiation.

The coldest part of the PFI structure is equipped with thermostat-controlled foil heaters to avoid subcooling under the allowable limits. The whole PFI is also protected against the convective cooling occurring during the ascent with an LLDPE film that acts as a wind shield, in the same manner as that for the electronics racks described above. A photograph of

**Fig. 6** PFI platform sitting on SUNRISE telescope before setting the protective wind shield

the PFI right before installing the wind shield can be seen in Fig. 6. The frame used to support it can also be observed.

*3.2.4 Data storage system.* A dedicated detailed thermal analysis of the DSS was carried out due to the criticality of this device. It consists of two units with 24 hard disks each, with a total capacity of $2 \times 2.4$ terabytes. Each unit is a pressurized cylindrical container, painted white to minimize thermal loads, with air inside. A fan helps the temperature to be almost uniform and avoid hotspots. The containers are located within the gondola frame to ensure mechanical protection during landing. They are placed behind the solar panels to avoid direct Sun illumination. A dedicated thermal test for the DSS was conducted in a thermal chamber to verify the thermal models and ensure the correct functioning of the system.

### 3.3 Thermal model

A geometrical mathematical model (GMM) with the geometry and the material thermo-optical and physical properties was set up. A point of uncertainty is the balloon-skin properties. The size of the balloon at float altitude, a diameter of about 130 m located about 60 m over the telescope makes its implementation in the model necessary since the radiative coupling with SUNRISE is expected to be significant, both direct IR exchange and reflecting Sun and Earth radiation. The balloon-skin is a composite material formed by three caps of 0.8 mil PE film. It has been modelled as described in Cathey [**9**], where the balloon is considered as a single-layer homogeneous material with equivalent properties. A summary of the thermo-optical properties of the main surfaces of SUNRISE, including the balloon, is presented in Table 1.

**Table 1** SUNRISE main surface thermo-optical properties

| Surface | $\alpha$ | $\varepsilon$ |
|---|---|---|
| White paint (Aeroglaze 276) | 0.23 | 0.9 |
| Silver teflon | 0.1 | 0.85 |
| Solar panel (front side) | 0.9 | 0.8 |
| Beta-cloth | 0.3 | 0.8 |
| LLDPE | 0.024 | 0.174 |
| Balloon skin | 0.1 | 0.3 |

For the two load cases defined in section 3.1, the external thermal loads for each node (solar, albedo, and Earth IR), the radiative couplings between nodes and part of the conductive couplings were calculated. The balloon float altitude used to calculate the thermal loads is 37.5 km.

The thermal mathematical model was built, adding to the previous results of the non-geometrical dissipating nodes (mainly inner nodes of electronics and gas nodes of pressurized vessels), the power dissipated at each node, and part of the conductive couplings between nodes, following the normal procedure in space thermal modelling. These last data were essentially thermal contact couplings, calculated using standard values for bolted boxes reported in Gilmore [**10**]. SUNRISE system level thermal model consists of about 2700 thermal nodes distributed, as indicated in Table 2.

### 3.4 Thermal model temperature predictions

The temperatures, gradients, and heat fluxes for the two load cases described above were calculated. In order to find a thermal design fulfilling the specifications, an iterative process was followed, modifying the design until an optimal satisfactory thermal solution was found. Among the different thermal solutions compatible with the thermal requirements, the configuration leading to minimum mass and minimum power consumption was chosen. An example of the necessary iterations that had to be carried out are: the location and orientation of the electronics racks, the arrangement of the boxes on the electronics rack, the use of thermal fillers for electronics boxes, the size of the PFI radiators, the PFI foam pieces thicknesses, etc. The software tool used to compute the temperatures was ESARAD/ESATAN, now ESATAN-TMS, a tool devoted to thermal modelling of spacecraft. In this tool, convergence is attained when the maximum iterative temperature change is less than a user-specified control constant value, in this case chosen as 0.001 K. The solution is checked with the relative energy imbalance, which should approach zero.

A thermal mapping of the temperatures predicted by the thermal models for both extreme scenarios can be found in Figs 7 and 8. Figures 7(a) and (b) are the front and back views for the hot case, respectively, whereas Figs 8(a) and (b) correspond to the cold case.

**Table 2** SUNRISE model nodal breakdown

| Subsystem | Nodes |
|---|---|
| Telescope (included sunshield) | 660 |
| Gondola structure | 219 |
| PFI electronics rack | 482 |
| Gondola electronics rack | 477 |
| PFI | 607 |
| DSS | 40 |
| Solar panels | 14 |
| Balloon | 4 |
| Crash pads | 24 |
| Convective shield | 88 |
| Others: batteries, motors, etc. | 93 |

## 4 FLIGHT DATA: COMPARISON WITH PREDICTIONS

SUNRISE was equipped with 256 temperature sensors aiming to monitor the thermal behaviour of the system. Temperatures were recorded every 3 s. The interest in monitoring temperatures has three purposes. First, a set of temperature housekeeping data was continuously sent to the ground station to know, in real time, the main temperatures of the system; second, the heaters located on the systems with risk of subcooling were thermostat controlled, and third, flight data provide priceless information to verify the thermal models and improve the knowledge of the thermal behaviour of the system, which will provide valuable information for future missions. Thus, following this third goal, the data provided by all the temperature sensors have been compared with the predicted values. More than 100 plots containing measured temperatures and the extreme values predicted by the model have been analysed. Most of the devices' temperatures are within the predicted range. Those out of range never jeopardized the mission. As expected, the temperatures of the devices located on outer surfaces exposed to the changing

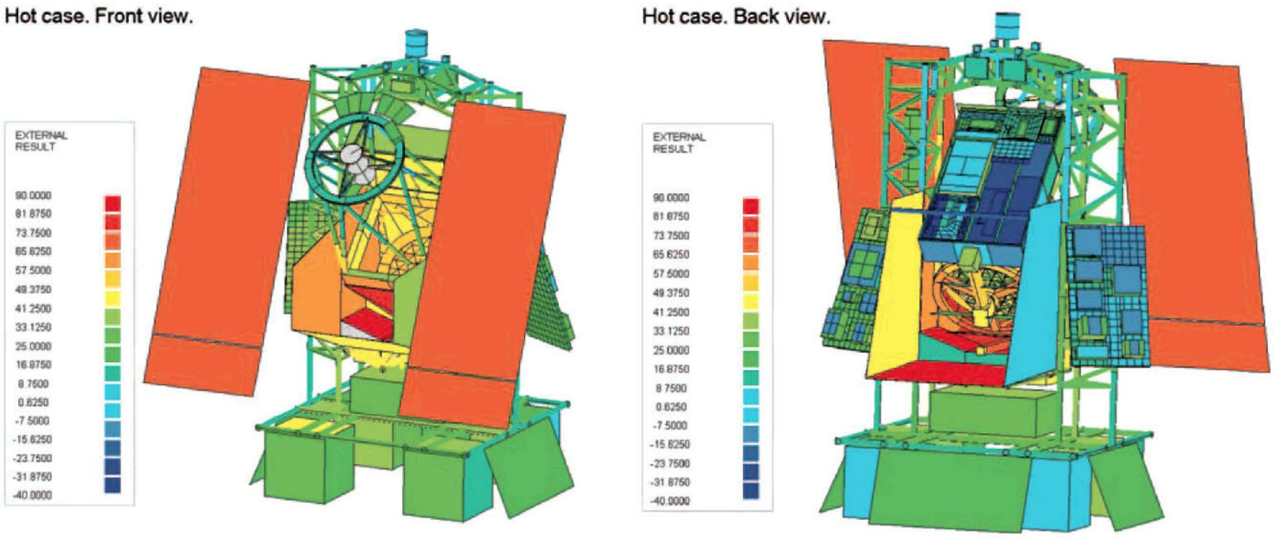


**Fig. 7** SUNRISE temperature mapping for hot case conditions: (a) front view, and (b) back view

environmental conditions fluctuated much more than the ones located within the system and therefore protected from the environment. The temperature excursions for most of the external devices were about 20 °C. This can be seen in Figs 9 to 14. In these figures, some selected records out of the more than 200 sensors are plotted, together with the model's extreme predicted values. In these figures, the *x*-axis represents time. It is coordinated universal time, not local time, and that is why the maximum and minimum temperatures separate from noon and midnight, respectively, as the balloon flies to the west.

It is important to stress that those day-to-night variations of about 20 °C are mainly due to the change in the albedo thermal load, dependent on the Sun elevation angle, since the rest of the loads remain almost constant during the cruise: the telescope is permanently facing the Sun. The Sun elevation changed from 3° to 43°

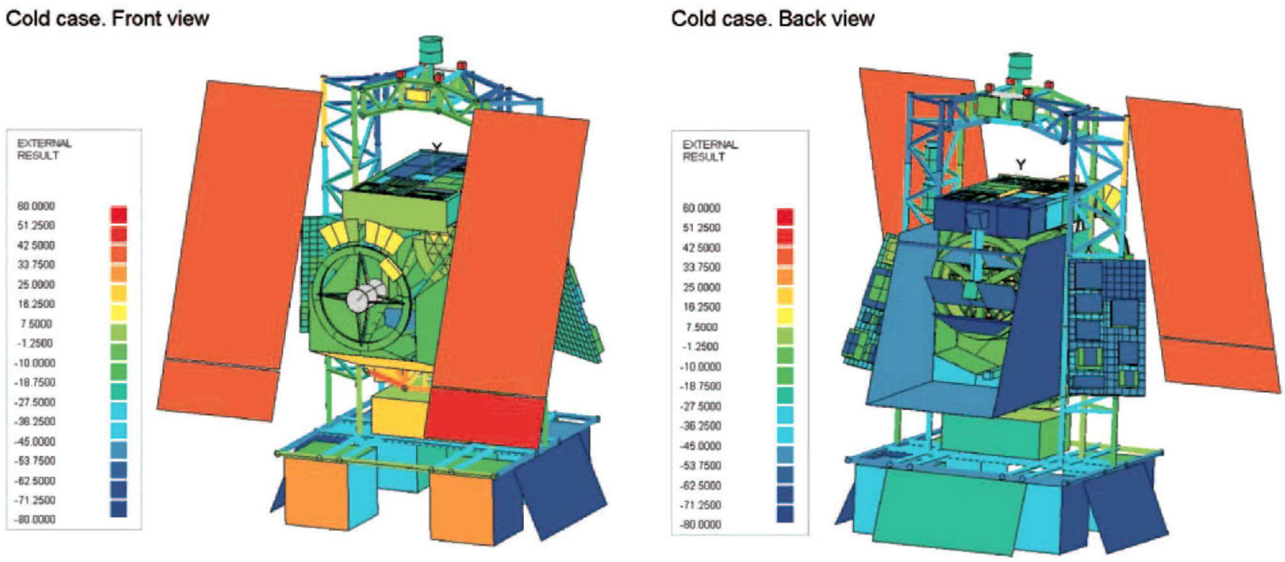


**Fig. 8** SUNRISE temperature mapping for cold case conditions: (a) front view, and (b) back view

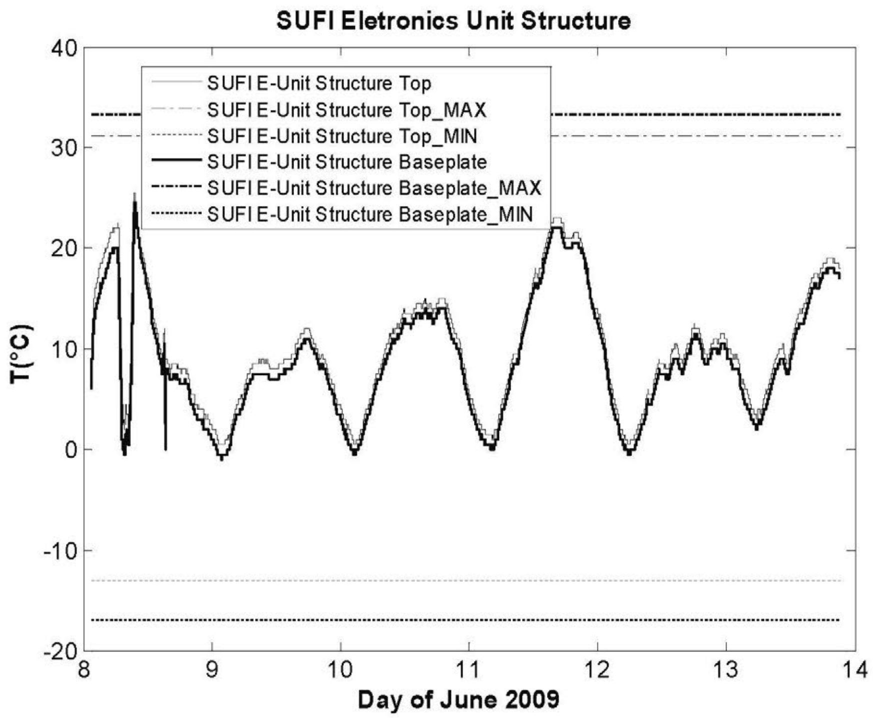


**Fig. 9** SuFI electronics unit flight temperature and hot and cold predictions. Note: temperatures correspond to the top surface and to the baseplate

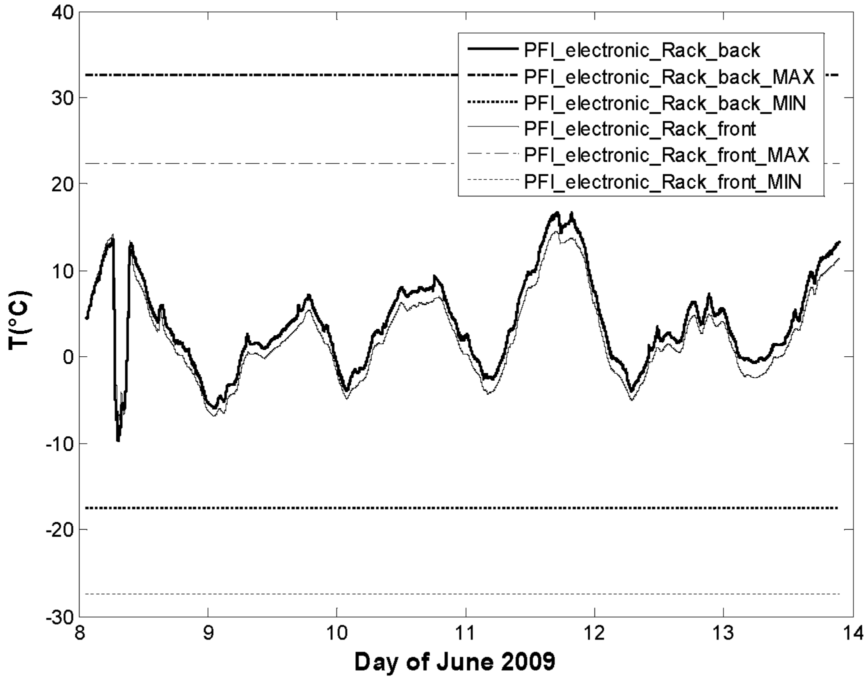


**Fig. 10** PFI electronics rack flight temperature and hot and cold predictions. Note: front and back temperatures are plotted

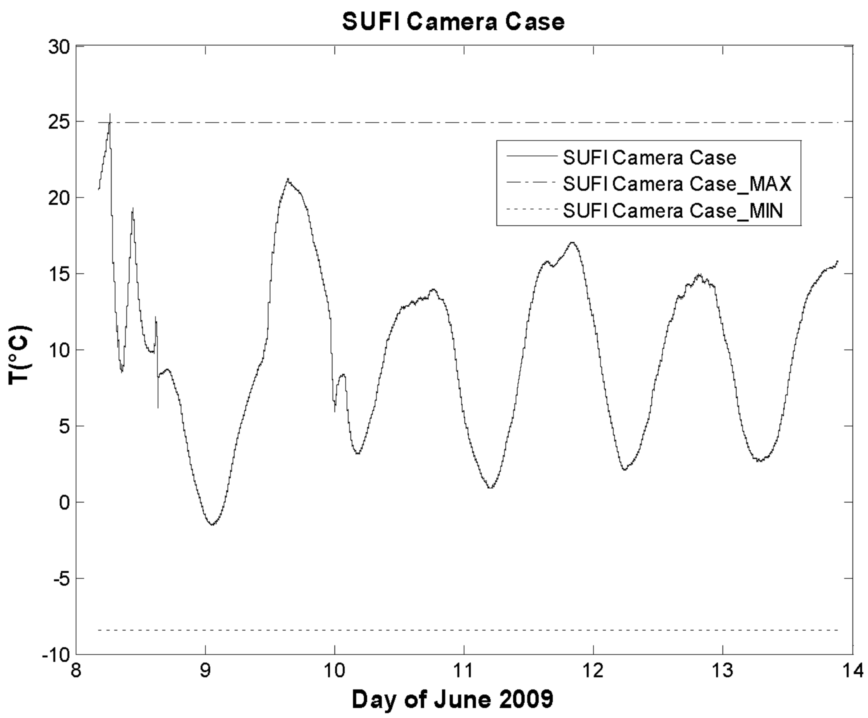


**Fig. 11** SuFI camera case flight temperature and hot and cold predictions. Note: front and back temperatures are plotted

during the mission and the albedo load approximately changes with the cosine of this angle.

Another fact to be noticed is that mean flight altitude during the cruise phase was slightly lower than expected, about 35.8 km, with a maximum of 37.4 km.

To compare flight temperature measurements with model predictions, in this article, units with

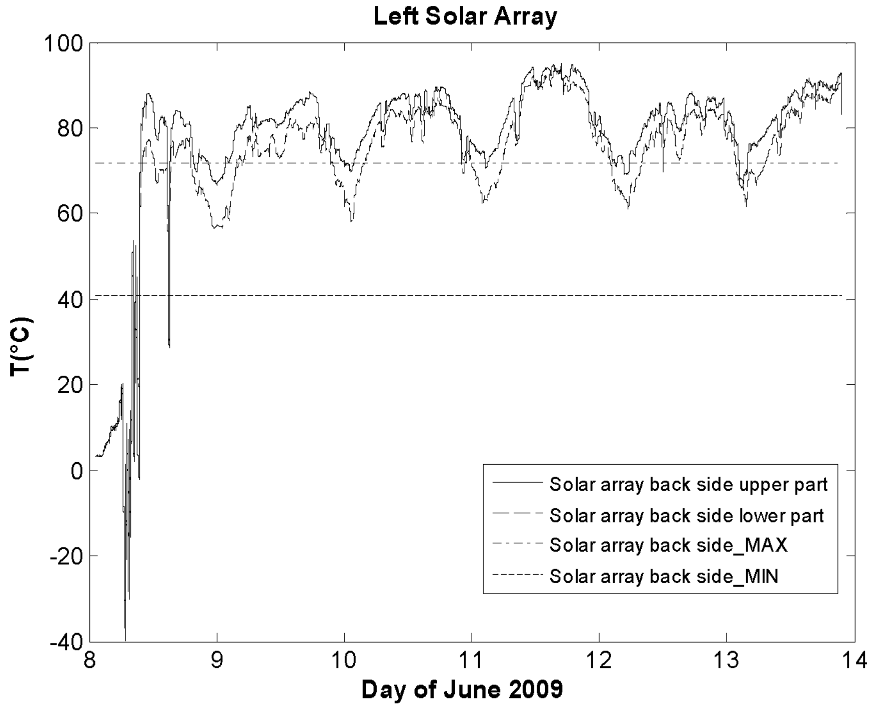


**Fig. 12** Solar arrays flight temperature and hot and cold predictions

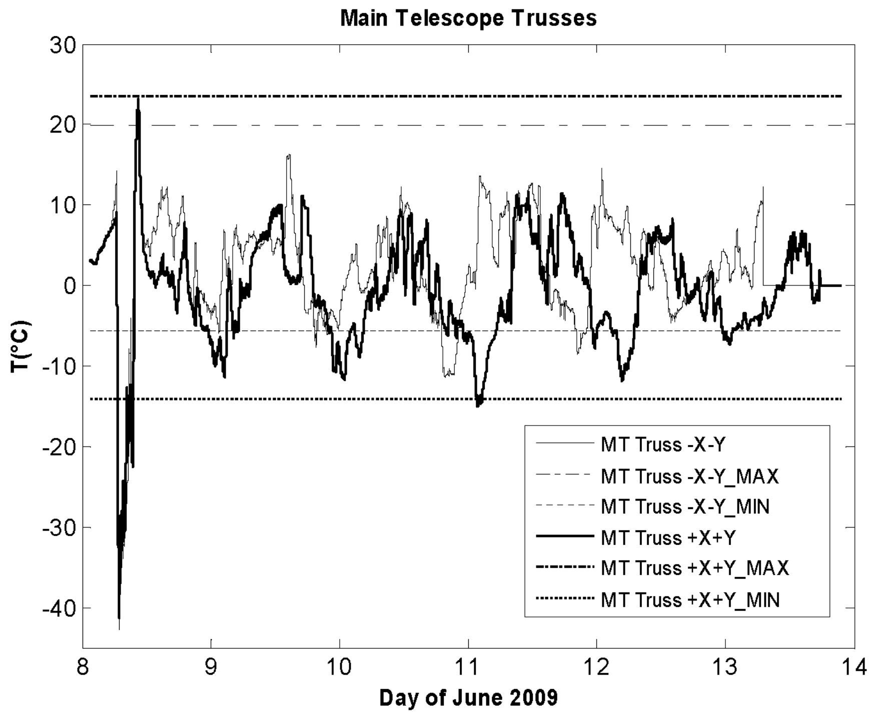


**Fig. 13** Telescope structure flight temperature and hot and cold predictions

different thermal behaviour have been chosen. Hence, one of the electronics boxes (ICU) mounted on the PFI electronics rack is plotted in Fig. 9; the PFI electronics rack structure, both front and back surfaces in Fig. 10; one of the units mounted on the PFI, the SuFI camera case in Fig. 11; the solar arrays in Fig. 12; the telescope structure in Fig. 13; and the DSS in Fig. 14.

When reading these figures, it is important to notice that measurements are not always

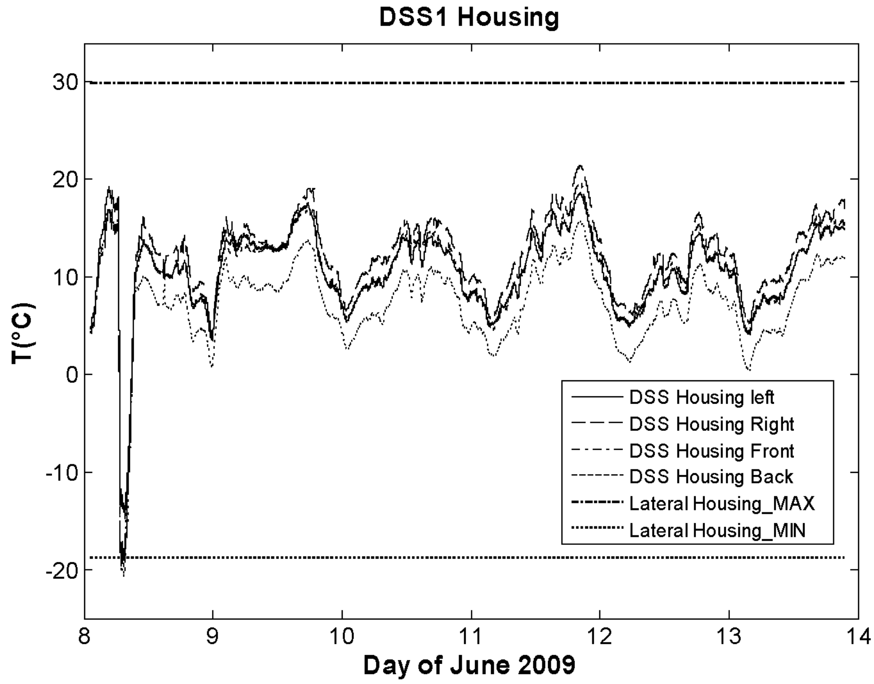


**Fig. 14** DSS housing flight temperature and hot and cold predictions

representative of the behaviour of one of the thermal nodes of the model. Hence, the correspondence between sensors and nodes is not always straightforward. This can lead to differences between model and flight data, a fact that has to be taken into account when analysing the data.

When these plots are examined, the first fact that can be appreciated is the right performance of the wind shield during the ascent phase. The launch took place on 8 June at 8:05 h. After about 3 h of climbing, continuously spinning, SUNRISE reached the float altitude. From the records, it is known that the minimum temperatures were reached about 1 h after the launch. Data presented in Figs 9 to 11 correspond to equipment protected with the wind shield. On the other hand, data presented in Figs 12 to 14 correspond to equipment directly exposed to the cooling air as the balloon passed through the tropopause. For the shielded devices, the temperature during the ascent hardly dropped below the minimum temperature reached during the cruise. This means that the wind shield performed as expected. However, the unprotected devices' temperatures dropped during the ascent to well below the minimum temperatures measured during the cruise. Hence, the solar panels reached almost $-40\,^{\circ}\mathrm{C}$ (minimum during the cruise was about $60\,^{\circ}\mathrm{C}$), the telescope structure reached also $-40\,^{\circ}\mathrm{C}$ (minimum during the cruise was about $-15\,^{\circ}\mathrm{C}$), and the DSS housing reached $-20\,^{\circ}\mathrm{C}$ (minimum during the cruise was about $0\,^{\circ}\mathrm{C}$). Therefore, this solution can be recommended for future balloon missions.

The most important point of discrepancy between the model and flight data is the temperature of the solar panels, as shown in Fig. 12. The measured temperature is higher than expected. It seems clear that the model assumptions were not the right ones. A lower real $\varepsilon$ value than the one used could be one of the reasons for this mismatch. Another significant difference is in the electronics rack structure. The temperature levels are well within the predicted range; however, the gradient across the 5-cm honeycomb is smaller than expected, as can be seen in Fig. 10. Differences not higher than $3\,^{\circ}\mathrm{C}$ were measured, while the predicted value reached almost $10\,^{\circ}\mathrm{C}$. Two reasons can explain this discrepancy. First, it could be also due to the wrong modelling of the solar panels. As they were hotter than expected, they heated the back surface of the racks and therefore, the gradients were smaller. Second, the empirical relationships used to model the thermal conductivity of the honeycomb [**10**] will be revised.

## 5 FINAL REMARKS

SUNRISE successfully completed his mission with all temperatures within the appropriate range throughout mission. In this article, the thermal design of the system has been presented aiming to help future balloon missions. The problems encountered during the design process have been reported, as well as the solution found. The use of the wind shield can be highlighted. The highly dissipating electronics needed direct view of cold sky to get rid of the dissipated power during the cruise phase. However, the cold air during the ascent phase would have led to too low temperatures. The LLDPE film, very transparent to IR radiation, has been presented as a possible solution for this problem.

Representative flight data have been presented and compared with model predictions. Most of the flight data kept within the predicted temperature ranges.


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